A RAND NOTE

AN EVALUATION OF ALTERNATIVE SAFETY CRITERIA
FOR NUCLEAR POWER PLANTS

Kenneth A. Solomon, Pamela F. Nelson

June 1982

N-1806-ORNL

Prepared for

The Oak Ridge National Laboratory

Rand
SANTA MONICA, CA. 90406

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 1982**	2. REPORT TYPE	3. DATES COVERED **00-00-1982 to 00-00-1982**
4. TITLE AND SUBTITLE **An Evaluation of Alternative Safety Criteria for Nuclear Power Plants**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **The Rand Corporation,Santa Monica,CA,90406**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **This report replaces ADE750828**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**82**	

This research was supported by the Oak Ridge National Laboratory under Contract No. 9025.

Published by The Rand Corporation

A RAND NOTE

AN EVALUATION OF ALTERNATIVE SAFETY CRITERIA FOR NUCLEAR POWER PLANTS

Kenneth A. Solomon, Pamela F. Nelson

June 1982

N-1806-ORNL

Prepared for

The Oak Ridge National Laboratory

Rand
SANTA MONICA, CA. 90406

PREFACE

This Note presents the first results of Rand's three-year study, begun in April 1981, on how probabilistic risk-assessment studies might be used effectively in the licensing of nuclear power plants. The study has two objectives: to assess criteria proposed for dealing with the question, "How safe is safe enough for the nuclear power industry?"; and to develop mechanisms by which the Nuclear Regulatory Commission can use this information in its decisionmaking and licensing processes. The Note reports the results of the first objective; a forthcoming study will outline the research currently under way in support of the second objective.

This study is supported by Oak Ridge National Laboratory Contract No. 9025.

SUMMARY

This Note assesses approximately 90 safety criteria and goals for the nuclear power industry that have been proposed over the past ten years in the U.S. and elsewhere. These criteria generally address the safety of nuclear power plants in terms of either reactor system safety, individual or societal risks, or in other measurable terms, such as dollar damage. We first categorize the criteria and then evaluate each item according to the following seven performance measures.

- How comprehensive is the criterion?
- Is it precise and unambiguous?
- How does it treat uncertain data and methodology?
- Is it realistic and practicable?
- Is it defensible?
- Is it simple and clearly understandable?
- Is it internally consistent?

In our analysis, three trends emerge:

1. Little consensus exists on what constitutes a universal risk criterion or on how to achieve such a criterion. Although criteria proposed by different individuals often differ by orders of magnitude, they may be based on equally plausible justifications. Conversely, numerically identical criteria might be based on rather diverse justifications. These factors underscore the highly subjective nature of the criteria selection process, a process that may not yield one single, universally accepted criterion.

2. No single criterion is both simple to understand and easy to implement; also, a mechanism for implementing the criterion is generally not offered.
3. None of the criteria can adequately accommodate uncertainty in the data. Although any valid criterion must place a bound on uncertainty, such uncertainty is inherent in any complex system and must be treated systematically.

This document arrives at a hybrid risk criterion made up of features of many of the criteria evaluated. (Because it is made up of features of criteria already proposed, rather than incorporating additional new features, the hybrid is not necessarily an optimal criterion.) This criterion's features resemble the specifications outlined for each of the performance measures, and as such it has the same shortcomings as those measures. With regard to each of the performance measures listed above, the hybrid criterion has the following specific qualitative features:

- Comprehensively addresses direct and indirect risk to society (here we consider primarily mortalities). Considering the direct risks, the criterion would be concerned with both immediate and delayed mortality and would consider not only the individual exposed to an average level of risk, but also to individuals exposed to higher levels. This hybrid criterion might also be concerned with secondary risks from evacuation, accident cleanup, and job relocations.

- o Simply, explicitly, and unambiguously justifies its basis; identifies and defends each of its assumptions; and explains clearly its limitations. (Uncertainty in both methodology and data base should be precisely accounted for by incorporating into the criterion a range of error bands.)
- o Practical, workable premise. It would be beneficial if such a criterion had been used before.
- o Defensible rationale that uses past experience either within the nuclear industry or some other industry with accident scenarios of similar potential, and one that specifies each of its assumptions clearly.

With a 95 percent band of confidence on information, quantitatively, this hybrid criterion might require the following. The probability of core melt per reactor year (R-Y) should fall between 1.0E-3 and 1.0E-4. For a marginal increase in an individual's annual mortality rate, the range might be between 2.0E-5 and 1.0E-6 per R-Y. For societal risk measured in person-rems, the range might be between 1000 and 10,000 per R-Y through about the year 2000. At that time, and depending on the size of the nuclear power industry, that range would have to be reevaluated.

Below we provide a basis for our selection of this hybrid according to its quantitative value and qualitative description. The basis for our quantitative range is simple and highly subjective. We consider those criteria that we judge best, group them, and specify the range in values that this group covers. Outliers are discarded if the range is much beyond an order of magnitude. The basis for our qualitative criteria is far more complex to describe.

- We believe that all components of a risk, including direct and indirect risks and immediate and delayed risks, are necessary for any decision between alternatives. For any specific alternative, the sum of all direct and all indirect risks reflects its total risk. Although two distinct alternatives may have similar direct risks, their indirect risks might be unique to a particular alternative.
- We argue for a very small or modest rate for discounting near-term risks and a zero or near-zero rate beyond a couple of generations. We think that risks to future generations are as important as risks to the present generation. Although an individual would certainly discount (i.e., wish to postpone) future risks, society as a whole would be less willing.
- We argue for a straightforward criterion because the more conditional the criterion, the more subject it would be to ambiguous interpretation.
- We argue for a proven criterion, since those that have been proven or time-tested are generally more appealing than those that are merely deduced.
- We endorse a criterion that avoids risk aversion because by properly accounting for all indirect risks of nuclear power and by selecting a rationale discount factor for future risks, including an additional risk-aversion factor is double counting.

ACKNOWLEDGMENTS

We appreciate the help of the many people who offered criteria and were interviewed during our evaluation. The time they spent explaining and clarifying their proposals was most valuable.

Special thanks are due our reviewers, William E. Kastenberg of The School of Engineering and Applied Sciences, University of California, Los Angeles, and Steven L. Salem, who offered helpful comments and guidance. We also gratefully acknowledge the assistance of our Project Manager at Oak Ridge National Laboratory, George Flanagan, who provided valuable comments and suggestions; Edward Merrow, Director of Rand's Energy Policy Program, whose guidance during the course of this study was most useful; and Charles L. Batten and Judy Rasmussen of Rand's Publications Department, who offered many valuable suggestions on writing style.

CONTENTS

FIGURES

TABLES

I. INTRODUCTION

In May 1979, the Advisory Committee on Reactor Safeguards (ACRS) recommended that "consideration be given by the NRC (Nuclear Regulatory Commission) to the establishment of quantitative safety goals for nuclear power reactors" and that "Congress should be asked to express its views on the suitability of such goals and criteria in relation to other relevant aspects of our technological society." Many groups, including the national laboratories, nuclear reactor vendors, architect-engineers, universities, private research organizations, and public interest groups have responded and continue to respond by proposing numerous safety criteria.

This Note reports the results of the first part of Rand's two-part, three-year research effort for Oak Ridge National Laboratory (ORNL). Part 1, initiated in April of 1981, assesses about 90 of the proposed safety criteria, specifically delineating each of the criteria, developing a set of performance measures, and evaluating them. Based on the evaluation, it identifies findings generic to each of the proposed criteria and specific to one or a few of them. By integrating the superior features of each of these criteria, Part 1 arrives at a hybrid criterion.

Here, we will discuss risk in terms of human mortality. Although dollar considerations will be presented, we do not intend to address the problems of judging lives and dollars at the same time. Therefore, we will usually discuss criteria in terms of various risk levels to individ-

uals or groups (e.g., society as a whole), and our evaluations will be made in similar terms.

HOW SAFE IS SAFE ENOUGH?

If we consider the issue of safety in and of itself, we might answer that question with "as safe as technologically possible," or "as safe as humanly possible." Some individuals might even argue that only "zero risk" is safe enough. Yet safety must be paid for either directly (in dollars) or indirectly (in diverted resources). And once we add this issue of cost, we see how difficult the question is to answer in that zero-risk safety carries with it an inestimable price tag.

To appreciate the complexity of the question, "How safe is safe enough?", consider the three-part experiment recently conducted by a Los Angeles reporter. To test the breaking-point of the two-liter bottle used by a soft drink manufacturer, this reporter loaded a few dozen bottles in the back of a station wagon. After a rough ride over potholes and around sharp curves at high speeds, each bottle emerged intact. Thus, they met some nominal level of safety. Next, the reporter dropped a few dozen of them from a helicopter hovering 100 feet above an asphalt pavement. Only one broke. He then put a two-liter bottle under a baby elephant's foot. It broke. This series of experiments demonstrates that at some point more stringent safety criteria may become impractical.

This need to balance safety against cost has in some sense been around for as long as technology itself. Early civilizations experienced it when they built structures: thicker walls offered greater

safety, thinner walls greater economy. We see it every day when we drive our cars. We trade off higher speeds and presumably greater convenience for reduced driving safety. The last few decades have focused this issue of safety versus cost in very specific technologies, such as nuclear power.

The first formal approach to balancing an acceptable level of safety against some reasonable cost came from the concept of the Maximum Credible Accident (MCA). This concept distinguishes between accidents that are so "sufficiently credible"--whatever that means--that they must be designed against, and those that are so "sufficiently incredible" that the cost of designing against them is not justified. This distinction is clearly subjective. Its weaknesses include the intuitive basis for its classification of accidents (Mitra et al., 1981), its failure to quantify safety, and its failure to recognize that although "incredible" accidents may have low frequency, they may pose a greater risk because of their proportionally greater consequences.

In an attempt to improve the MCA approach, the Design Base Accident (DBA) approach evolved. This approach principally identifies low-frequency, high-consequence events that must be protected against. Although subjective judgment on what is credible and what is incredible is avoided, subjectivity and intuition still prevail in the identification of accidents included in the design base. This approach still lacks a systematic, formal, probabilistic method to determine the frequencies and consequences of accidents. Such a method would be an improvement, since the accidents considered would be based on numerical estimates of which might be most important in terms of human life. That

is, given an adequate data base, such a formal, probabilistic method could help reduce the subjectivity that remains in the current DBA approach.

The NRC's present statutory mandate in licensing nuclear power plants is similarly subjective. It issues an operating license based on a reasonable assurance that the authorized activities can be conducted without endangering the health and safety of the public. The NRC has not yet quantified terms like "adequate" and "reasonable" on the basis of accident frequency and consequence.

In recognition of a need to quantify standards of safety, the Advisory Committee on Reactor Safeguards (ACRS) recommended in May 1979 that quantitative safety goals be considered in the licensing and operation of nuclear power plants. These NRC recommendations stimulated much activity. The NRC's System Reliability Research Branch instituted and supported research and development programs to apply risk analyses more widely and to evaluate implications of numerical risk criteria. Numerous other groups initiated and supported such studies as well. These groups include the public utilities, the Electric Power Research Institute, national laboratories, universities, and private research foundations.

Clearly, there are advantages and disadvantages to having various organizations proposing quantified safety criteria. The more people think about the problem, the more good ideas and points of view are expressed. Unfortunately, many of those ideas and points of view are inconsistent. Deciding which are best is the aim of the present study.

SCOPE OF THIS STUDY

Sections II, III, and IV address the three primary tasks of Part 1 of the study. Section II presents approximately 90 of the proposed risk criteria, categorizing them by their applicability to the reactor system, the risk to an individual at the site boundary, or the risk to society as a whole. The criteria are arranged on the basis of who proposed them, the technical factors that they consider, and whether they take into consideration specific subjective and economic factors. Technical factors that may be considered include: accident probability, accident consequence, number of people exposed to the risk, whether some segment of this population is more vulnerable than another, how uncertainty in risk data is handled, and so on. These criteria may be expressed in both quantitative and qualitative terms.

Section III identifies a set of performance measures for evaluating each of the criteria identified earlier. These performance measures include: 1) Does the criterion consider a range of societal risks? 2) How easily can a criterion be implemented? 3) How simply can it be expressed? 4) How does it treat uncertainty in data and methodology? 5) Is its interpretation ambiguous or unique? 6) Is the criterion internally consistent? 7) Is it defensible? Recognizing the possible ambiguity in these measures and in the manner in which they might be applied, Section III also contains an evaluation of the proposed criteria. It identifies two sets of findings: those that are generic to most or all of the proposed criteria and those that are specific to one or a few.

We divide Section IV into four subsections. First, we examine the extent to which an optimal criterion could be defined. Second, we qualitatively describe a hybrid criterion made up of the best features of those criteria that we have already evaluated. Third, we offer a quantitative range. And, finally, to the extent we can, we defend this hybrid.

II. THE RISK CRITERIA

To make some sense of the various definitions of risk criteria, we must first arrange them systematically, identify the elements that those definitions do and do not consider, and examine the similarities and differences between the criteria. Rather than describe each proposed criterion in detail, this section looks at the range of responses.

Before discussing the criteria themselves, we will place them in the context of current approaches to reactor safety. We have already pointed out the current use of the Design Basis Accident approach, even though it lacks a quantitative basis. We then mentioned that a formal probabilistic methodology, known as Probabilistic Risk Assessment (PRA), would be a useful way to reduce the subjectivity in current safety approaches. In fact, any effort at actually calculating a numerical level of safety, either to establish a safety criterion, or to assess current levels of safety, must ultimately depend on probabilistic analyses of these sorts, because of the wide levels of uncertainty in available data, phenomenology, and methodologies.

And what information do we now have concerning current levels of safety in nuclear power plants? The most extensive study conducted to date, the Reactor Safety Study (WASH-1400), used a probabilistic framework to evaluate the safety of the two major commercial reactor types in the United States. We summarize those results here and later use them as reference points for the criteria.

With regard to the probability of a reactor core melting, WASH-1400 derives the following probability estimates:

2.3E-6 for the hardware contribution to core melt.

1.2E-6 for the human contribution to core melt.

3.5E-6 for the total contribution to core melt.

5.0E-5 for the "best estimate" value.

4.0E-5 for the 50 percent confidence level (see Bhattacharyya, 1981).

4.0E-4 for the 95 percent confidence level (see Bhattacharyya, 1981).

Considering individual mortality risk at a reactor site boundary as a result of potential accidents, WASH-1400 estimates

> 2.0E-10 for the risk of early fatality per reactor year per individual exposed. For an estimated 15 million affected individuals and a total of 100 reactors at 66 sites, this is a societal risk of 3.0E-3 early fatalities per year.

Finally, considering the risk to society due to the incidence of latent cancer fatalities resulting from nuclear reactor accidents, we can infer a rate from WASH-1400, of

> 7.0E-4 latent cancer fatalities per reactor year, per year, or about 2.0E-3 total latent cancer fatalities per reactor year of operation, over a 30-year latency period following exposure.

As we discuss the criteria themselves, it is not surprising to note that many are expressed in terms comparable to these, since, for a criterion to have value, it must be measured against something. Most individuals or organizations offer several criteria, and the range in their

proposals generally reflects varying confidence bounds in the PRA, different estimates in number of reactors on line in a future year, and different classes of criteria themselves.

This section classifies risk criteria according to level of safety involving

- o Reactor systems
- o Individuals at or adjacent to the reactor site
- o Society as a whole
- o Qualitative criteria and criteria concerned with property damage.

REACTOR SYSTEM SAFETY

All proposed criteria dealing with system safety establish safety bounds based on core-melt probabilities. Core melt is the single most important accident, since it is the accident that primarily contributes to radioactive release. As such, it has received significant attention from those who suggest risk or safety criteria.

Table 1 summarizes 30 criteria (column 1), proposed by 11 investigators, organizations, or individuals (column 2) for the frequency of core melt (cm) or core degradation (cd)--a less serious situation. The bases for their proposals are also cited (column 3). Figure 1 displays the information presented in Table 1.

The proposed criteria range widely, from 5.0E-7 to 4.5E-3 core melts per reactor year (R-Y) for reactors of 1 gigawatt (GWe) size. Thus, these criteria range both above and below the WASH-1400 reference points; that is, safety levels for currently operating reactors appear

Table 1

CRITERIA FOR THE FREQUENCY OF CORE MELT PER REACTOR YEAR

CORE MELT PER R-Y(a)	SOURCE	BASIS(b)	FREQUENCY OF AT LEAST ONE ACUTE FATALITY PER R-Y(c)
1.0E-4	ACRS (NUREG-0739)	Hazard state d, goal level for large-scale fuel melt.	
5.0E-4	ACRS (NUREG-0739)	Hazard state d, upper limit for large-scale fuel melt.	
3.0E-4	ACRS (NUREG-0739)	Hazard state c, goal level for significant core damage.	
1.0E-3	ACRS (NUREG-0739)	Hazard state c, upper limit for significant core damage.	
1.0E-4	(AIF, 1981)	Atomic-Industrial-Forum. No basis given.	
5.0E-7	(Burns, 1979)	5% chance of core melt during life of industry (i.e., 300 reactors x 300 years).	
2.5E-5	(Burns, 1979)	Alternate criterion. One accident in 40,000 reactor years.	
1.0E-6	(Bhattacharyya, 1981)	Mean frequency.	
5.0E-3	(Griesmeyer, 1979) (Mitra, 1981)	Hazard state c, less than one significant core damage in 5 lifetimes (200 years).	
1.0E-3	(Griesmeyer, 1979) (Mitra, 1981)	Hazard state d, less than one large-scale fuel melt in 25 lifetimes (1000 years).	

TABLE 1 (cont.)

CORE MELT PER R-Y(a)	SOURCE	BASIS(b)	FREQUENCY OF AT LEAST ONE ACUTE FATALITY PER R-Y(c)
4.5E-3	(Mitra, 1981)	Unacceptability limit based on maximum likelihood of two accidents (Brown's Ferry and Three Mile Island) in 440 reactor years (Light Water Reactors through 1979).	9.1E-5
5.5E-4	(Mitra, 1981)	95% confidence level based on above.	1.1E-5
2.2E-3	(Mitra, 1981)	$750 million core damage, .32 mills/ KWH differential cost between nuclear and coal, 1 GWe plant operating at 60% present capacity.	
1.7E-3	(Mitra, 1981)	Same as above, except assuming $1 billion damage.	
1.0E-4	NRC (<u>Inside NRC</u>, 1981a)	Estimated mean probability of annual power plant accident that results in a large-scale core melt.	
3.0E-4	O'Donnel (Bhattacharyya, 1981)	Mean frequency.	
1.0E-3	(Vesely, 1980)	Operational design criterion.	
1.0E-4 <1.0E-3	(Vesely, 1980)	Warning range, accounting for human error.	
1.0E-5	(Vesely, 1980)	System and component failures.	
1.0E-6 <1.0E-5	(Vesely, 1980)	Warning range, not accounting for human error.	

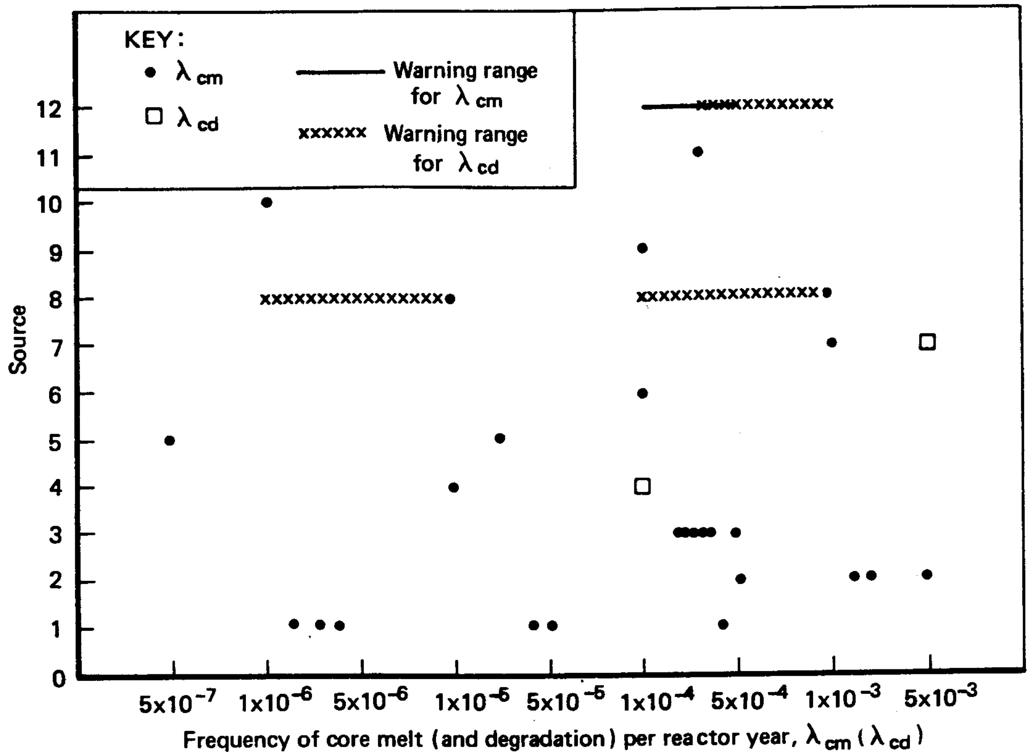
TABLE 1 (cont.)

CORE MELT PER R-Y(a)	SOURCE	BASIS(b)	FREQUENCY OF AT LEAST ONE ACUTE FATALITY PER R-Y(c)
1.0E-5	(Wall, 1979a)	Some fraction of 5.0E-4 used in WASH-1400.	2.0E-7
1.0E-4	(Wall, 1979b)	Criterion for cladding degradation.	
5.0E-4	(Zebroski,1980)	One core melt in the next 30 years (moratorium at 65 LWRs).	4.0E-6
3.3E-4	(Zebroski,1980)	Chance of core melt<1 in 3 in next 10 calendar years, using low estimate of reactor years in the next 10 years.	
3.1E-4	(Zebroski,1980)	Same, using medium estimate of reactor years.	
2.9E-4	(Zebroski,1980)	Same, using high estimate of reactor years.	
2.5E-4	(Zebroski,1980)	Chance of core melt under 66% next 20 calendar years, using low estimate of reactor years in next 20 years.	
2.3E-4	(Zebroski,1980)	Same, using medium estimate of reactor years.	
2.1E-4	(Zebroski,1980)	Same, using high estimate of reactor years.	1.0E-5
5.0E-7	(Zebroski,1980)	5.0E-4 x 1/1000 probability of radiation release to the public from a core melt.	

NOTE: The parenthetical entries in the SOURCE column correspond to similar entries in the References.

(a) R-Y is defined as a reactor year. The reactor is assumed to be 1 GWe in size.
(b) Hazard state c assumes >10% of noble gas inventory leaking into primary coolant. Hazard state d assumes >30% of the oxide fuel becoming molten.
(c) Based on 2% probability of a fatality, given a core melt.

ACRS = Advisory Committee on Reactor Safeguards
NRC = Nuclear Regulatory Commission



The list of authors of quantitative core melt criteria is not complete, but includes experts in the field

1 Wash-1400 (Ref. points)	7 Greismeyer
2 Mitra	8 Vesely
3 Zebroski	9 NRC
4 Wall	10 Corkerton
5 Burns	11 O'Donnel
6 Atomic Industrial Forum (AIF)	12 Advisory Committee on Reactor Safeguards

Fig. 1--Frequency of core melt (λ_{cm}) and core degradation (λ_{cd}), by source

to meet some criteria, but fail others. (Current estimates of core-melt probability range between 4.0E-4 to 8.0E-4 core melts per R-Y.)[1]

The bases for these criteria vary. As a conservative or upper bound, most who offer proposals use the probability of a single core melt in the entire reactor industry over a period of time; some use a monetary criterion of some sort; one uses as a basis the accidents at Brown's Ferry and Three Mile Island; and some use no apparent basis whatsoever. A few use a high, moderate, and low set of estimates that span up to three orders of magnitude.

As discussed in Levine (1981), three or four of the proposals examine reactors on a case-by-case basis. These proposals are by the Advisory Committee on Reactor Safeguards (ACRS) or (NUREG-0739) in our References; UKAEA in Kinchin (1979), and The United Kingdom Central Electricity Generating Board in Corkerton (Bhattacharyya, 1981). The proposal by Joksimovic (1980) may also be applicable in this way.

The ACRS proposal makes specific reference to the use of its component decision rules in conjunction with plant-specific PRAs as a licensing tool for new reactors. The decision rules proposed cover more potential safety-related aspects of risk than any other proposals, and are more stringent than current rules.

Both British proposals are primarily concerned with supporting specific plant-licensing decisions. As Levine (1981) notes, because of

---

[1] Noting the overlap between core-melt criteria and estimates of core-melt probability, we see that some criteria would indicate that the current generation of reactors is unsafe. Our interpretation is different; we argue that those reactors that might not meet the standard should be cost effectively redesigned to meet this criterion. (The details of such an assessment, however, are beyond the scope of this study.)

the differences in licensing practices between the United States and the United Kingdom, the British proposals are not particularly applicable to our needs. Bhattacharyya's goal is being used as the basis for licensing the new advanced gas-cooled reactors.

Kinchin does not explicitly state the purpose of his proposal. Levine (1981), however, contends that Kinchin's intention would be to use the goal on a plant-by-plant basis. Kinchin's proposal has not yet been adopted by the British regulatory authorities.

Levine (1981) states that the AIF (1981) proposal is aimed at overall regulatory decisionmaking, but not plant-specific licensing decisionmaking for levels of overall safety. AIF suggests that the direct application of PRA and Safety Goals in specific plant-licensing process decisions is premature at this time.[2]

Like Kinchin, Joksimovic does not specifically state a particular purpose in his proposal. But Levine (1981) reports that the intent of the Joksimovic proposal is aimed primarily at the regulatory process, and not at licensing.

Levine contends that safety proposals should not be used at this time in the licensing of individual reactors. He describes how specific PRA studies have been properly used by the NRC in making sound decisions on reactor safety. He further notes that to make full use of such risk assessments it is necessary to establish quantitative safety levels.

Levine notes that the basis of Starr and Whipple's proposal (to be discussed later) is quite different from his own. Starr and Whipple

[2] Although licensing is part of the regulatory process, we distinguish here between plant-specific licensing considerations and generic regulatory considerations.

observe that because of the costliness of major nuclear plant accidents, steps must be taken to ensure against them. To compensate for the inequitable risk to those who live close to a reactor site, they propose a utility rate credit.

For a set of core-melt probabilities, Mitra et al. (1981) set an acceptability criterion based on estimates of at least one fatality induced by core melt per R-Y. Based on the simplistic assumption (from WASH-1400) that there is a 2 percent probability of a fatality given a core melt, column 3 in Table 2 displays Mitra's criterion for at least one fatality per reactor year. This number varies between roughly one in ten thousand to two in a hundred million--a range so great that its value might be insignificant.

RISK TO INDIVIDUALS AT OR ADJACENT TO THE REACTOR SITE

The risk to individuals at or adjacent to the reactor site is defined as the marginal increase in annual mortality risk per individual exposed. Units are most often expressed as mortalities per R-Y; one person offers a criterion in units of millirems (mrem).

Table 2 and Figure 2 demonstrate that the proposed criteria for individual mortality risk per R-Y range between 1.0E-8 and 1.0E-4 (Table 2, column 1), all well above the WASH-1400 estimate. The bases for these proposed criteria vary (Table 2, column 3). A total of 22 individual risk criteria are offered by 15 individuals and organizations.

Table 2

CRITERIA FOR INDIVIDUAL MORTALITY RISK AT REACTOR SITE

RISK PER R-Y or S-Y(a)	SOURCE	BASIS
5.0E-6 per S-Y	ACRS (NUREG-0739)	Delayed fatality goal level for maximally exposed individual.
2.5E-5 per S-Y	ACRS (NUREG-0739)	Delayed fatality upper limit for maximally exposed individual.
1.0E-6 per S-Y	ACRS (NUREG-0739)	Early fatality goal level for maximally exposed individual.
5.0E-6 per S-Y	ACRS (NUREG-0739)	Early fatality upper limit for maximally exposed individual.
1.0E-5	(Adams & Stone, 1967)	An incremental increase in an individual's chance of death per year that is smaller than the demographic variation. In the United Kingdom, that chance of death per year is inappreciable and acceptable.
1.0E-5 per S-Y	AIF (Inside NRC, 1980a)	Early and latent fatality risk to maximally exposed average individual, goal level.
1.2E-6	(Atchison, 1979)	Canadian safety requirements for licensing of CANDU nuclear power plants: Average annual dose of 9 mrem/yr x 130 delayed deaths - 1.0E-6 person rem.
1.0E-5	(Bowen, 1975)	Early and delayed fatalities. Aim is to have a small chance (i.e., 1%) of a large catastrophe in a lifetime.
1.0E-7	(Burns, 1979)	Delayed death to 300 million people, and 30 total deaths per year.
1.0E-4	ICRP (Inside NRC, 1980b)	Acceptable risk for radiation worker.
RISK PER R-Y or S-Y(a)	SOURCE	BASIS
1.0E-5	ICRP (Inside NRC, 1980b)	Acceptable risk for maximally exposed individual.

Table 2 (Cont.)

1.0E-6	Inter-Organizational Working Group	Likelihood of a lethal dose (200-400 whole body rem) to any nearby resident.
1.0E-4	(Joksimovic, 1980)	Early and latent fatality.
1.0E-6	(Kinchin, 1979)	Early fatality. International Commission on Radiological Protection (ICRP) states that 1.0E-6 to 1.0E-5 should be acceptable. Webb and McLean state that 1.0E-6 does not play a part in individual decisionmaking.
3.0E-5	(Kinchin, 1979)	Delayed fatality. Based on factor of 30 disparity.
1.0E-6	(Mitra,1981)	One% of lowest death risk (10-year-old Caucasian female) of 1.0E-4.
1.0E-5	(Mitra,1981)	95% confidence level of above.
5.0E-6 to 1.0E-5	NRC (<u>Inside NRC</u>, 1981a)	Mean probability of early and delayed fatality from an accident to an individual living or working in the vicinity of the plant site throughout their lives.
1.0E-8	(Starr, 1981)	Early and latent fatality goal level.
1.0E-4	(Starr, 1981)	Early and latent fatality upper limit.
1.0E-8	(Wall, 1979a)	Early death. No basis given.
2.0E-5	(Maxey, 1982)	Early plus delayed fatality; derivable from a dose criterion.

NOTE: The parenthetical entries in the SOURCE column correspond to similar entries in the References.
(a) All criteria are given in units of R-Y (reactor years) unless specified as S-Y (site years).

ACRS = Advisory Committee on Reactor Safeguards
AIF = Atomic Industrial Forum
ICRP = International Committee on Radiological Protection
NRC = Nuclear Regulatory Commission

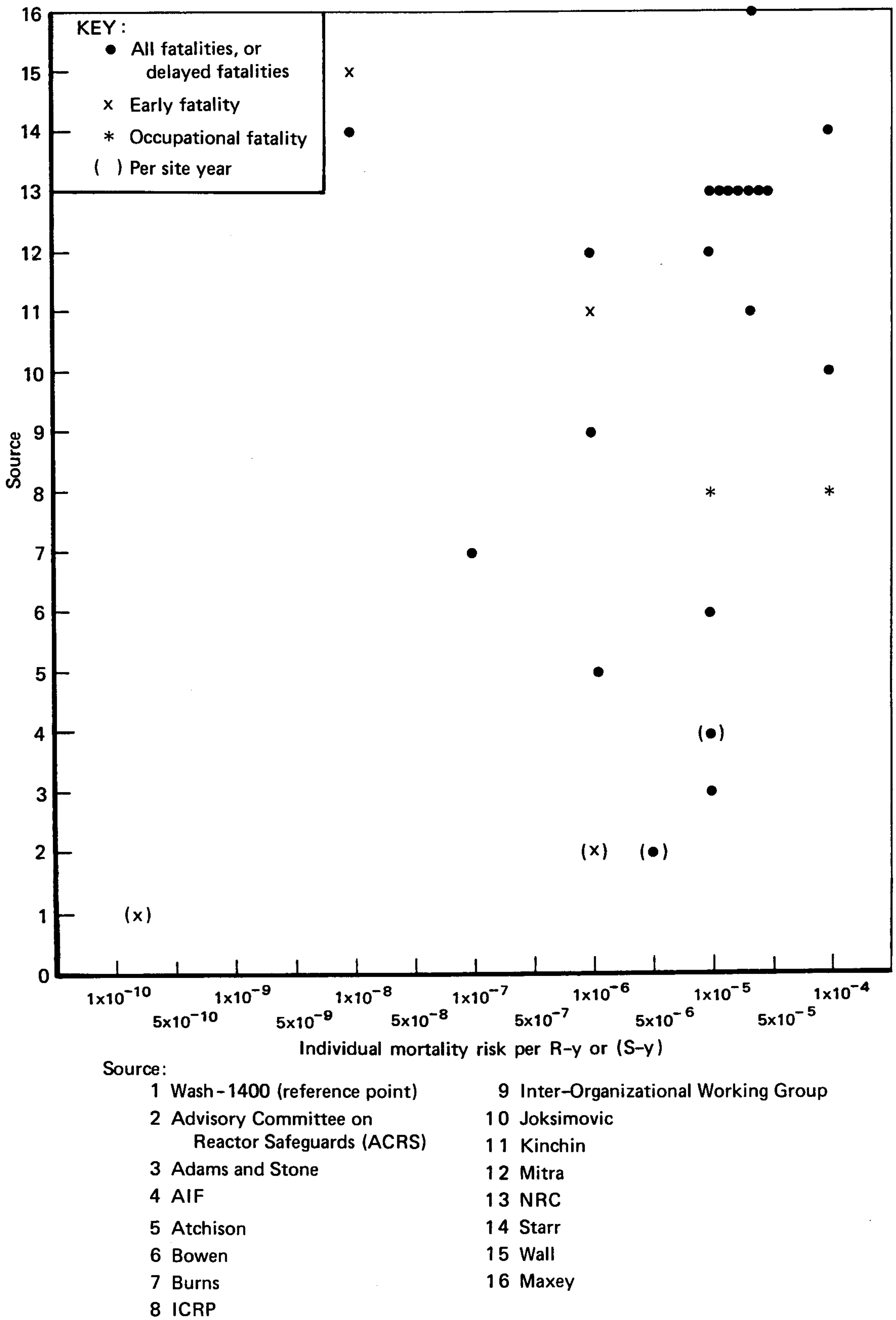


Fig. 2--Criteria for Individual Mortality Risk at Reactor Site Boundary, by Source

Two types of individual mortality criteria are offered: those concerning immediate or early mortality and those concerning only delayed mortality. For immediate or early deaths among the general population, the proposed criteria range from 1.0E-8 (Wall, 1979a) to 1.0E-4 (Joksimovic, 1980), all less stringent than the 2.0E-10 which we infer from WASH-1400.

Among the criteria proposed for immediate or early death, most individuals report a mean value, and some bound their proposals by also reporting a confidence interval. For example, Mitra et al. (1981) report a criterion with a mean value of 1.0E-6 mortality rate per R-Y, derived by taking 1 percent of the gross mortality rate of a 10-year-old Caucasian female (the lowest of any human mortality range). This mean value assumes limited information regarding the exposed risk. For situations involving a 95 percent confidence in information, Mitra et al. propose 1.0E-5. The Advisory Committee on Reactor Safeguards (ACRS) also tentatively proposes two criteria: 1.0E-6 as the proposed goal and 5.0E-6 as the proposed upper limit, both for the maximally exposed individual (NUREG-0739).

Although some people distinguish between an early and a delayed death criterion, others do not. Starr (1981) proposes a criterion of 1.0E-8 for early and delayed death as a goal and 1.0E-4 as an upper limit. Here we should note that the difference between the ACRS goal level and upper limit is only a factor of 50, whereas the corresponding difference between the Starr proposals is a factor of 10,000. Although we have no rationale for judging which of these two factors makes more sense, we believe that a factor as large as 10,000 might mask any bene-

fits achieved from having a quantitative criterion. Joksimovic also proposes identical numbers for early and delayed deaths, that is, 1.0E-4.

Kinchin (1979) and the WASH-1400 reference results distinguish between early and delayed mortality (i.e., they discount delayed deaths). For the delayed mortality rate, Kinchin (1979) proposes a factor of 30 less stringent than that for immediate mortality. Griesmeyer et al. (1979) suggest two other factors. They recommend a factor of 5 for individual risk, and based on other information they supply, we can infer a ratio of about 7 or 8 for societal risk. In the latter case, Griesmeyer et al. apply a risk aversion factor for early fatalities for the societal criterion, thus increasing the "future discounting" of latent fatalities.[3]

Although we are not sure of the precise logic used by Kinchin (1979) and by Griesmeyer et al. (1979), we believe that the potential effect of discounting future risks is too huge to be treated in a casual fashion. Such a discounting concept must be thought out carefully and must distinguish between societal and individual discounting of risk. (We shall treat the issue of discounting in a future document.)

One of the more refreshing criteria offered comes from Maxey (1982). This very straightforward proposal suggests that an acceptable

---

[3] We detect a logical error with the argument of Griesmeyer et al. Setting aside their rather large values for discounting future risks, we might expect that individual risk rather than societal risk would have a higher discount factor. We contend that the individual would have a greater incentive than society as a whole to postpone his or her risk. As an example, all other things equal, an individual would strongly wish to postpone his or her mortality from age 50 to age 80. On the other hand, an excess societal mortality rate of 1 percent is equally serious if it happens today or in 30 years.

criterion would be one that is roughly equal to the variance across the country in background radiation dose. If we assume that this variance is 200 milli-rems (a rem is a unit of biologically assessed dosage of radiation) (actually, the variance is larger if we take the most extreme low dose and the most extreme high dose), and using a standard dose-response relationship by assuming one excess fatality per 10,000 person-rems, we find that Maxey's criterion reduces to 2.0E-5 mortality risk per R-Y.

For delayed mortality among occupational workers, the proposed criteria are less conservative; only the International Committee on Radiological Protection (ICRP) (_Inside NRC_, 1980b) proposes 1.0E-4 per reactor year.

Table 2 summarizes a variety of other proposals for individual mortality risk per R-Y.

SOCIETAL RISK

Many people proposed criteria specifying acceptable levels of societal risk. Here we define societal risk as the sum total of all the risks to all affected individuals, and calculate it as the product of _the total number of people exposed_ and _the radiation dose per person_ integrated over time of exposure. Table 3 and Figure 3 express this risk in terms of person-rems per R-Y, and in cases of (immediate) thyroid cancers or cases of latent thyroid fatalities (LTF) per 1.0E+10 kilowatt hours.[4] Based on individual risk criteria and assuming a set of standard populations around a reactor site, societal risk criteria in

[4] 1.000 GWe R-Y = 0.874E+10 kilowatt hours.

Table 3

CRITERIA FOR SOCIETAL RISK

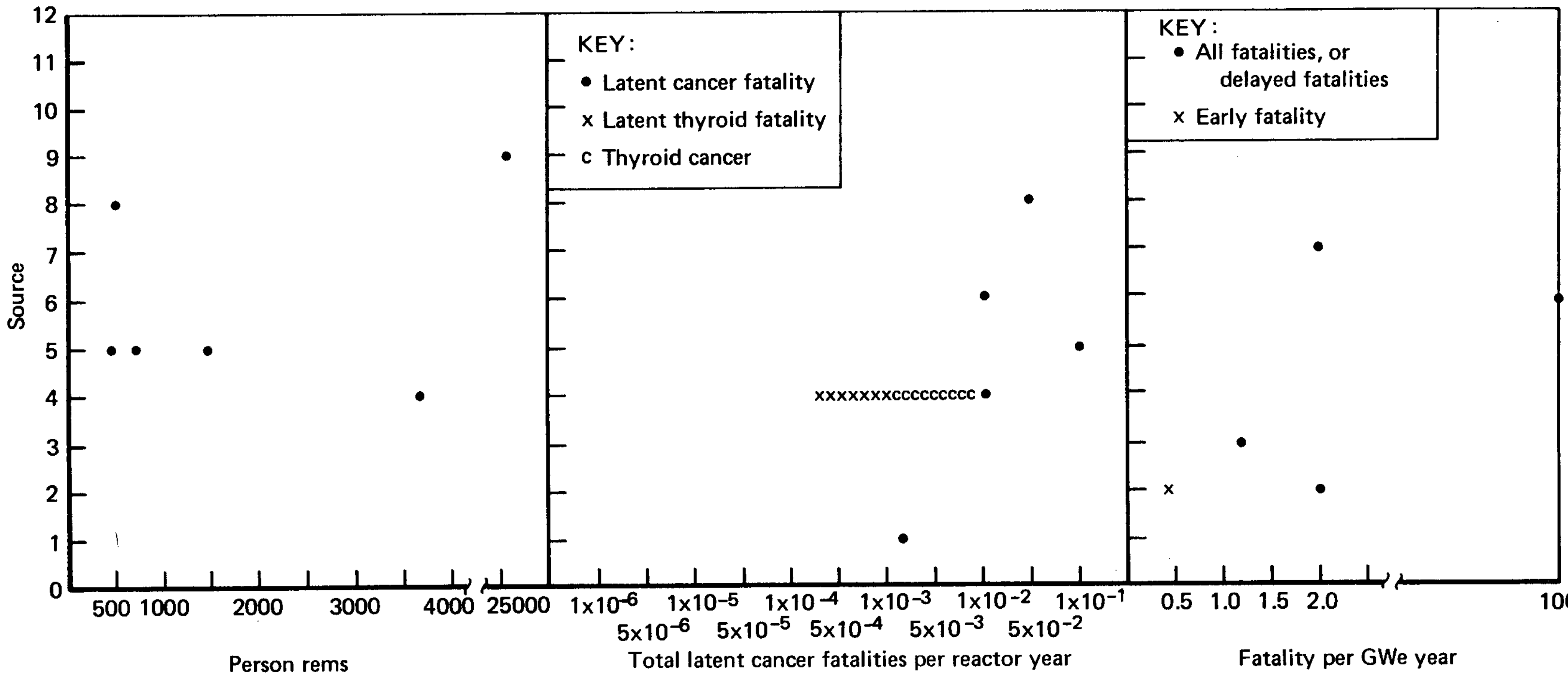
RISK PER R-Y (FATALITY PER 1.0E+10 KWH)	SOURCE	BASIS
(2)	ACRS (NUREG-0739)	Delayed fatality goal level.
(10)	ACRS (NUREG-0739)	Delayed fatality upper nonacceptance limit.
(0.4)	ACRS (NUREG-0739)	Early fatality goal level (with risk aversion).
(2)	ACRS (NUREG-0739)	Early fatality upper nonacceptance limit (with risk aversion).
(1.2)	(AIF, 1981)	Not mentioned if delayed or early fatality. Since delayed death is the dominant societal risk, public fatality may be construed as latent fatality.
<.1 fatalities per GWe year	AIF (Inside NRC, 1980a)	
3667 person-rems	(Atchison,1979)	Canadian Reactor Siting Guide.
1.2E-2 Latent Cancer Fatalities (LCF)	(Atchison,1979)	1 Latent Cancer Fatality (LCF) per 10,000 person-rems during 30-year period.
0.0018-0.0110 thyroid cancers	(Atchison,1979)	0.5-3.0 thyroid cancers per thyroid rem.
0.00025-0.0015 Latent Thyroid Fatalities (LTF)	(Atchison,1979)	Mortality rate of 0.04 for children under 10 (15% of population) and .15 for remainder.
0.10 LCF	(Burns,1979)	1.0E-7 LCF per person, 300 reactor years
500 person-rems	(Burns,1979)	5000 person-rems per LCF, 300 million population, 300 reactors.

Table 3 (Cont.)

RISK PER R-Y (FATALITY PER 1.0E+10 KWH)	SOURCE	BASIS
750 person-rems	(Burns,1979)	5000 person-rems per LCF, 300 million population, 200 reactors.
1500 person-rems	(Burns,1979)	5000 person-rems per LCF, 300 million population, 100 reactors.
.01	(Joksimovic, 1980)	Total LCF based on "no identifiable public injury" for an accident with a probability of 1.0E-4 per R-Y. (With risk aversion for higher consequence accidents.) (Figure 4)
Comprehensive risk curves	(Kinchin,1979)	Site-specific criterion. Complementary cumulative distribution factor.
Comprehensive risk curves	(Levine,1980)	Interim safety goal. 1/10 the level of lowest non-nuclear risk from WASH-1400 (i.e., risk of death for persons on ground from aircraft crashes. Year criterion.)
<2/GWe year	NRC (Inside NRC, 1981a)	Statistically estimated mean fatalities.
500 person-rems	(Wall,1979a)	Expected accidental population dose.
0.05 LCF	(Wall,1979a)	Based on 1 LCF per 1.0E-4 person-rems.
25,000 person-rems	(Zebroski, 1980)	10% probability per failure of population receiving this dose.

NOTE: The parenthetical entries in the SOURCE column correspond to similar entries in the References.

ACRS = Advisory Committee on Reactor Safeguards
AIF = Atomic Industrial Forum
NRC = Nuclear Regulatory Commission



Source:

1 Wash-1400 (reference)
2 ACRS
3 AIF
4 Atchison
5 Burns
6 Joksimovic
7 NRC
8 Wall
9 Zebroski

Fig. 3--Criteria for Societal Risk, by Source, per Reactor Year

terms of deaths per reactor year can also be inferred from Table 2.

The annual person-rem dose proposals vary between 500 (Burns, 1979) and 25,000 (Zebroski, 1980) and are based on a variety of factors. Burns considers that the number of reactors in the country vary between 100 and 200. Zebroski bases his criterion on the probability of a 10 percent chance of the population receiving a radiation dose following an accident.

Only the Canadians propose a criterion based on the incident rate of thyroid cancer (Atchison, 1979). They propose a rate of between 0.0018 and 0.0110 per R-Y.

A variety of proposals based on incident rate of latent cancer fatalities (LCF) is reported. The Canadians propose an LCF of 0.012 per R-Y. They base this on the assumption that 1 LCF is caused per 10,000 person-rems of exposure, spread over a 30-year period of latency following the exposure. Wall (1979a) and Burns (1979) propose LCFs of 0.05 and 0.1 per R-Y, respectively. These are all less stringent than the WASH-1400 results, from which we infer an estimate of about 0.002 total LCFs per year of operation.

One factor that can be applied to societal risk is risk aversion. This factor generally represents an individual's or society's acceptance or rejection of differing risks on the basis of such factors as the nature of the risk, its early or delayed effect, the nature of its consequences, and so on. In the discussion on individual risk, risk aversion factors of up to 30 were mentioned in weighting delayed risks less importantly than immediate risks. Here, we also mention society's aversion to high-consequence risks. That is, a single, large event with

a potential number of casualties is generally considered more undesirable than several smaller events whose total probability and total casualties are the same as those for the single large event.

Griesmeyer et al. (1979) and the ACRS (NUREG-0739) findings present a model that accentuates the undesirability of high-consequence risks. Although they suggest a numerical value of 1.2 for their risk-aversion parameter (1.0 would imply no aversion and less than 1.0, a preference), they also point out that the very simplicity of this model negates its usefulness over the range of societal attitudes toward various levels of consequences. We agree.

The explicit recognition of this numerical factor is indicated in Table 3 for the ACRS criteria (NUREG-0739). Joksimovic (1980) uses a similar model with an equivalent factor of 1.5. Others may or may not have factored risk aversion into their choices for specific numeric goals.

In our review of the risk-aversion literature (see Salem et al., 1980), we could not locate a consistent set of factors leading to a unique numerical value. Choosing a single number, we believe, might bias the criterion. We find this factor to be sensitive to the size of the accident, the nature of the accident, and the subjectiveness of the interpretation.

QUALITATIVE CRITERIA AND CRITERIA BASED ON DOLLAR DAMAGE

Table 4 and Fig. 4 present both qualitative criteria and criteria that assess dollar damage. For example, the Atomic Industrial forum (AIF, 1981) proposes that the incremental cumulative risk due to nuclear power plants should be a "small" fraction of average background health

Table 4

QUALITATIVE CRITERIA AND CRITERIA BASED ON DOLLAR DAMAGE

SOURCE	COMMENTS	SYSTEM	INDIVIDUAL	SOCIETAL	$
ACRS (NUREG-0739)	Early fatality valued at $5 million per life saved. Delayed fatality valued at $1 million per life saved. Property damage = twice economic loss.				x
(Adams & Stone, 1967)	Incremental increase in individual's chance for death per year less than demographic variation in UK. Societal criterion not useful because of uncertainty in potential number of casualties. Policy did not consider property or other resource damage.		x	x	
(Maxey, 1982)	The allowable dose should equal the variance in dose likely to be seen across the country. No uncertainty considerations were given.		x		
(AIF,1981)	No individual should bear an inordinate risk. The incremental cumulative risk should be a small fraction of average background incidence of health hazards. Goal should promote rational allocation of resources to reduce public risk to achieve optimum benefit attainable for the cost. $100/person-rem. $1 million per life saved.		x	x	x
AECC (*Nucleonics*,1980c)	Safety responsibility must rest with the licensee. *Defense-in-depth approach*.	x			
(Atchison, 1979)	Process system failure = 1E-2 to 1E-4/yr. Special safety system failure = 1E-3. Dual failure = 1E-5 to 1E-7/year.	x			
Eklund (*Nucleonics*,1980c)	Not enough experience.	x			

Table 4 (Cont.)

SOURCE	COMMENTS	SYSTEM	INDIVIDUAL	SOCIETAL	$
ICRP (*Nucleonics*, 1980b)	Goal is to see risk of death to radiation worker less <u>than or equal to that of safe industry worker</u>.		x		
(Joksimovic, 1980)	Figure 4				x
(Kaplan, 1981)	Only infinite safety is safe enough. Benefits are not considered.		x	x	
Levenson & Rahn	Number of acute fatalities and injuries 6 months after accident.			x	
NRC (*Inside NRC*, 1981a)	Presently employs system unavailability (i.e., single failure criterion) in licensing process. Limits overall risk, but not sufficient.	x			
	"Members of the public should be provided a level of protection such that no individual bears a significant risk to life and health."		x		
	"Societal risk associated with nuclear power plant operation should be as small as can be reasonably achieved and should, in any event, be consistent with the risks of competing technologies for generating electricity."			x	
OTA, 1981	Four approaches to standardization: 1) Universal software practices, 2) rush NRC's program, 3) safety block concept for standardization of systems, and 4) selection of single design.	x			

Table 4 (Cont.)

SOURCE	COMMENTS	SYSTEM	INDIVIDUAL	SOCIETAL	$
(Rowsome, 1980)	Short-term goal: chance of significant accident up to .2 percent in time between completion of short-term fix and end of plant life.	x			
(Slovic, 1980)	Risk statistics have little utility as guides to nuclear safety policies. Need to minimize probability of small accidents. Risks perceived as unique, uncontrollable, unknown, potentially catastrophic, and dreaded.			x	
	Greatest cost of an accident is public relations and effect on nuclear future.				x
(SRP, 1975)	The only specific proposal for quantifying component availability criteria for diesel-generator reliability testing. Goal is .99 at nominal 50% confidence level.	x			
(Zebroski, 1980)	For a core melt, design must provide 1 in 1000 chance of protection. Stabilize above goal for 10 years; beyond 1990, consider higher goals. Recurrence frequency of 50 years, 1 in 5000 chance of public protection.	x			
	1% probability per failure that any person receives >5 rems.		x		
	10% probability per failure that total population dose >25,000 person-rems.			x	
	Need to increase resources on existing domestic energy.				x

NOTE: The parenthetical entries in the SOURCE column correspond to similar entries in the References.

ACRS = Advisory Committee on Reactor Safeguards
AECC = Atomic Energy Commission of Canada
ICRP = International Committee on Radiological Protection
NRC = Nuclear Regulatory Commission
OTA = Office of Technological Assessment

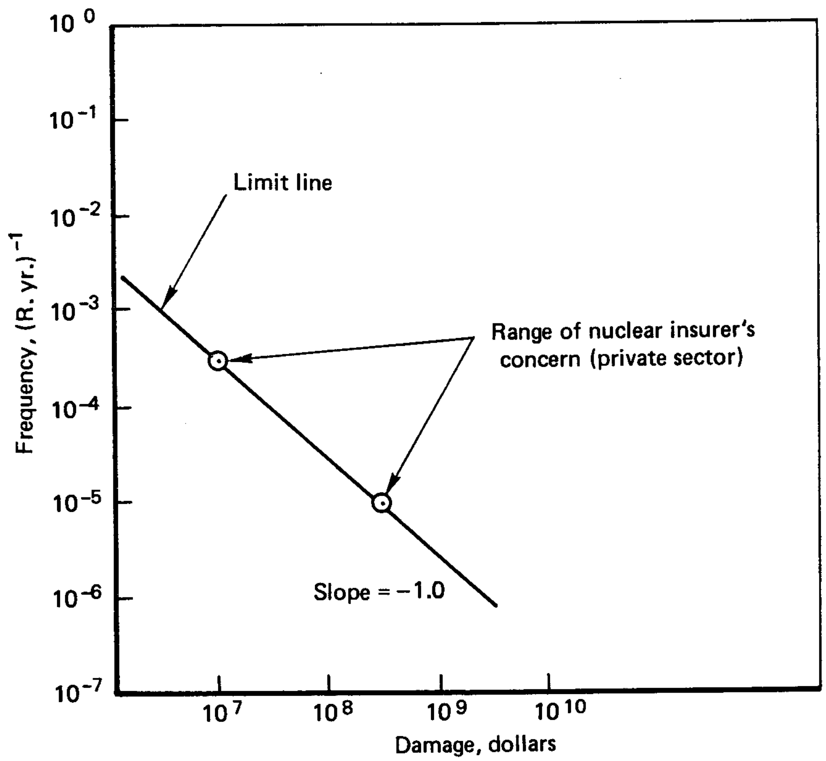


Fig. 4--Quantitative Safety Goal for Public Property Risk Proposed by Joksimovic (1980)

effects. Recall that this position is similar to Maxey's (1982). Similarly, Adams and Stone (1967) propose that the incremental increase in an individual's fatality rate per year should be less than the demographic variation in risk across the United Kingdom.

Kaplan, in interpreting the question, "How safe is safe enough?" states that, objectively, the only risk universally acceptable is zero

risk, a condition that he recognizes as unachievable due to a variety of factors (Kaplan, 1981).

Others use cost considerations in their criteria. However, since our general concern here is with quantitative criteria based on human mortality, we will not specifically evaluate these criteria as we do those in Tables 1-3; Table 4 shows a range of other types of criteria that have been proposed.

Although this study is concerned with human mortality as the basis for the criteria and performance measures it discusses, one cost consideration should be discussed: cost-benefit approaches to risk reduction. In general, such approaches imply trade-offs between the costs of safety improvements and the benefits received. Weighing the cost of safety systems against the costs saved (in terms of system reliability and availability gains), this may be feasible though complex. However, because it considers costs of improvements versus lives saved, the process is the subject of much debate. Ultimately, the question becomes, "What is the dollar value of a human life?" In NUREG-0739, early fatalities are valued at $5 million per life, and delayed fatalities at $1 million. The AIF (1981) uses $1 million per life saved. Salem et al. (1980) point out other values that have been used; for example, the National Highway Traffic Safety Administration has found that reduction in highway fatalities has cost $287,175.00 per life saved.

How can cost be factored into safety criteria? It is possible to ignore it completely. In our evaluations in Section III, we are not concerned with whether costs or other bases were used in determining a

specific criterion, only whether a rational basis was used. In nuclear reactor safety, one often-cited basis is the ALARA ("as low as reasonably achievable") criterion. That is, additional safety systems or improvements should be incorporated into a plant as long as each can reduce the risk by an additional, cost-effective increment. Thus, the test of whether additional systems are necessary is whether a lower level of risk is "reasonably (i.e., cost effectively) achievable." In the case of nuclear reactor licensing, "reasonable" has been temporarily defined, at least in one case, to avoid argument. This has been set at \$1,000.00 per person-rem of exposure (Code of Federal Regulations, 10 CFR 50, Appendix I). In very rough terms, this could correspond to \$10 million per life saved, assuming about 1 excess fatality per 10,000 person-rems.

The merits of such considerations, however, need not be weighed against those of alternative criteria that are based solely on human life. The two concepts may actually be combined. For example, an ALARA criterion could be incorporated into a wide range of criteria, such as reduction of risk to a level as low as reasonably achievable below a specific risk level. Thus, even though a plant might meet a certain required level of safety, it would have to make further improvements if additional risk reduction was shown to be cost effectively achievable. Such action would also assure the utilities that non-cost-effective measures would not be required at a later date.

III. THE EVALUATION

This section evaluates each of the proposed criteria that we have tabulated. First, we define the metric used to make the evaluation--the performance measures. Next, we caution readers about the inevitable shortcomings of such an evaluative approach. Finally, we apply the performance measures and evaluate each criterion.

EVALUATION BASED ON PERFORMANCE MEASURES

Some of the safety criteria proposed in Section II have attributes that are clearly superior to others. To more explicitly rank or evaluate the performance of each criterion, we must identify the superior attributes that could comprise the "perfect" criterion and assess how the criterion measures up to those desired attributes.

Those positive attributes are what we call *performance measures*. We expect that the most useful criteria will contain most of those attributes. The seven performance measures used here are as follows:

1. Does the criterion comprehensively address all risks, including direct and indirect risks, immediate and delayed effects? Although no single criterion addresses all aspects of direct and indirect risks, those that address more are rated higher. Direct risks are defined as those risks that are directly caused by the accident. They include risks that result from exposure to radiation, both occupational and general population exposure. This exposure may result in immediate and delayed effects. Indirect risks result from the accident; these

include risks to individuals cleaning up after the accident, and injuries and mortalities related to evacuation. They may also include property damage and loss of a resource, such as agricultural land, lakes, and so on.

2. Is the criterion precise and unambiguous? Will all people interpret it in exactly the same way? The need for consistent interpretation is obvious; one would want consistent interpretations over time, across designs, and across individuals. The more specifically defined the criterion, the more unambiguous the interpretation.
3. Does the proposed criterion treat data and methodological uncertainty, and if so, to what extent? Can the criterion deal with undefinable factors? Uncertainty plays a major role in the risk caused by a technology and in the perception of that risk by the general population.
4. Is the criterion realistic and practical? If the proposed criterion requires the impossible, its application may achieve nothing useful. For example, criteria are unrealistic if they demand zero risk or if they set a specific goal within too small a margin of uncertainty.
5. Is the criterion defensible? That is, what is the rationale behind the criterion? For example, an often-quoted criterion suggests that delayed death from cancer is more desirable than immediate death. Proponents of this position claim that specific numbers can be inferred, but they fail to distinguish between what society might judge as best for people as a whole

and what a single individual might judge as best for himself or herself. Defensible criteria describe both the logic used to arrive at them and the assumptions used to support them. (For example, assumptions dealing with the number of nuclear reactors on line should be specified.)

6. Is the criterion simple? Is it clearly understandable? To what extent is the criterion consistent with intuitive judgment? Counter-intuitive criteria are less readily implemented and accepted.

7 Is the criterion internally consistent? A criterion is internally inconsistent in that it may specify two or more criteria that do not reduce to a common number. A criterion that specifies both individual and societal risk without specifying the societal population is an internally inconsistent criterion. All those who offer criteria that appear in more than one table among Tables 1, 2, and 3 are inconsistent. This seventh performance measure is not shown in the tables; instead, it is discussed in the next subsection.

USE OF THE PERFORMANCE MEASURES

Each of the performance measures plays a role in deciding which of the criteria in Section II is likely to be most useful in deciding what constitutes an appropriate level of safety. Before applying these performance measures to each of the criteria, however, it must be emphasized that these measures are far from perfect.

First, the performance measures are often interconnected. For example, two of the measures are "simple" and "unambiguous." Although these measures are somewhat distinct, a criterion that is unambiguous would correlate with one that would be simple. Second, the list of performance measures is necessarily incomplete. There are other ways of assessing the criteria, such as explicit public acceptability. But such a parameter is difficult to measure, and public acceptability is implied in several performance measures. Third, the relative importance of each measure is subject to interpretation. (Which is more important, defensibility or simplicity?) Fourth, the documentation on each of the criteria differs. Some are documented extensively; others are not. And, finally, both the evaluation process and the measures are highly subjective. In fact, one rather curious result of the evaluation process is that although two or more proposed criteria might be quantitatively identical, they may be qualitatively very different. This dichotomy comes about because the bases used by proposal makers in arriving at their criteria might be very different, some bases being far superior to others.

If they are all so difficult to separate from one another and judge on their merits, why use the performance measures? They allow us to distinguish between promising proposals and ones that could be dismissed easily, and could provide a basis by which to formulate a hybrid criterion made up of the best features of each criterion. The very process of examining the criteria and evaluating their aggregate features allows us to combine and eliminate some criteria.

THE EVALUATION

The evaluation process is highly qualitative and subjective. It places each criterion and measure in a matrix and assigns a "+", "0", or "-" rating to each matrix element. The grades are relative: "+" means the criterion meets the performance measure better than most other criteria do; "0" suggests that it may meet it in part; and "-" means that it either barely meets the performance measure or does not meet it at all. This qualitative rating scheme distinguishes between practical and impractical criteria, as shown in Tables 5A, 5B, and 5C. Specific examples of ratings for each of the first six performance measures are given below.

Table 5A shows the evaluation of the core-melt criteria, whereas Tables 5B and 5C, respectively, illustrate the evaluations of individual and societal risk criteria. Entries in Table 5A are given in units of core melts per R-Y; entries in Table 5B in units of marginal increase in mortality risk per R-Y. Entries in Table 5C are given in one of four units: LCF, thyroid cancers, and person-rems per R-Y if they are not enclosed by parentheses, and LCF per 1.0E+10 kilowatt-hours if they are enclosed by parentheses.

When there is more than one criterion from a single source, the ratings for performance measures 1 through 6 are often identical. Exceptions to this general rule come about when the criteria being assessed are derived from different considerations.

However, when multiple criteria appear across more than one table, the ratings for performance measure number 7 (internally consistent) is almost consistently "-". This "-" rating comes about because these mul-

Table 5A

EVALUATION OF CORE-MELT CRITERIA

Source	Criterion	Performance Measure*					
		1	2	3	4	5	6
ACRS	1.0E-4	0	+	0	+	-	0
ACRS	5.0E-4	0	+	0	+	-	0
ACRS	3.0E-4	0	+	0	+	-	0
ACRS	1.0E-3	0	+	0	+	-	0
AIF	1.0E-4	0	-	0	+	0	0
Burns	5.0E-7	0	+	0	-	0	+
Burns	2.5E-5	0	-	0	-	0	+
Bhatta-charyya	1.0E-6	0	0	-	-	0	0
Griesmeyer	5.0E-3	0	+	0	+	-	0
Griesmeyer	1.0E-3	0	+	0	+	-	0
Mitra	4.5E-3	+	+	-	+	0	0
Mitra	5.5E-4	+	+	+	+	0	0
Mitra	2.2E-3	+	+	-	+	0	+
Mitra	1.7E-3	+	+	-	+	0	+
NRC	1.0E-4	0	-	-	+	0	0
O'Donnel	3.0E-4	0	0	-	0	0	0
Vesely	1.0E-3	0	0	0	-	0	0
Vesely	1.0E-4< 1.0E-3	0	0	+	-	0	-
Vesely	1.0E-5	0	0	0	0	0	-
Vesely	1.0E-6< 1.0E-5	0	0	+	-	0	-
Wall	1.0E-5	0	0	0	-	0	0
Wall	1.0E-4	0	+	0	+	0	0
Zebroski	5.0E-4	0	0	0	+	0	0
Zebroski	3.3E-4	0	0	+	+	0	0
Zebroski	3.1E-4	0	0	+	+	0	0
Zebroski	2.9E-4	0	0	+	+	0	0
Zebroski	2.5E-4	0	0	+	+	0	0
Zebroski	2.3E-4	0	0	+	+	0	0
Zebroski	2.1E-4	0	0	+	+	0	0
Zebroski	5.0E-7	0	0	+	+	0	0

*NOTE: The performance measures used in this table may be identified as follows: 1) comprehensive; 2) unambiguous; 3) uncertainty treated; 4) practicable; 5) defensible; 6) simple; 7) internally consistent (not shown in table).

ACRS = Advisory Committee on Reactor Safeguards
AIF = Atomic Industrial Forum
NRC = Nuclear Regulatory Commission

Table 5B

EVALUATION OF INDIVIDUAL RISK CRITERIA

Source	Criterion	Performance Measure*					
		1	2	3	4	5	6
ACRS	5.0E-6	+	0	0	+	0	0
ACRS	2.5E-5	+	0	0	+	0	0
ACRS	1.0E-6	+	0	0	+	0	0
ACRS	5.0E-6	+	0	0	+	0	0
Adams&Stone	1.0E-5	0	-	0	+	0	+
AIF	1.0E-5	+	0	0	+	0	0
Atchison	1.0E-6	0	0	0	+	0	0
Bowen	1.0E-5	+	-	0	+	0	0
Burns	1.0E-7	0	-	0	-	0	0
ICRP	1.0E-4	0	0	0	0	0	0
ICRP	1.0E-5	0	0	0	+	0	0
Inter-Org.	1.0E-6	0	+	0	+	0	0
Joksimovic	1.0E-4	+	0	0	-	0	0
Kinchin	1.0E-6	+	0	0	+	-	0
Kinchin	3.0E-5	+	0	0	+	-	0
Maxey	2.0E-5	0	+	-	+	0	+
Mitra	1.0E-6	+	-	+	+	0	0
Mitra	1.0E-5	+	-	+	+	0	0
NRC	1.0E-3	+	0	0	0	0	0
Starr	1.0E-8	+	0	0	-	0	+
Starr	1.0E-4	+	0	0	-	0	+
Wall	1.0E-8	0	-	0	-	0	0

*NOTE: The performance measures used in this table may be identified as follows: 1) comprehensive; 2) unambiguous; 3) uncertainty treated; 4) practicable; 5) defensible; 6) simple.

ACRS = Advisory Committee on Reactor Safeguards
AIF = Atomic Industrial Forum
ICRP = International Committee on Radiological Protection
Inter-Org. = Inter-Organizational Working Group
NRC = Nuclear Regulatory Commission

Table 5C

EVALUATION OF SOCIETAL RISK CRITERIA

Source	Criterion	Performance Measure*					
		1	2	3	4	5	6
ACRS	(2)	+	0	+	0	0	+
ACRS	(10)	+	0	+	0	0	+
ACRS	(0.4)	+	0	+	0	0	+
ACRS	(2)	+	0	+	0	0	+
AIF	.1/GWe yr.	0	-	-	0	-	0
Atchison	3667 rems	0	0	0	0	0	0
Atchison	1.2E-2 LCF	0	0	0	0	0	0
Atchison	0.0018-0.011	0	0	+	0	0	0
Atchison	.00025-.0015	0	0	+	0	0	0
Burns	0.10 LCF	0	0	0	0	0	0
Burns	500 rems	0	0	0	0	0	0
Burns	750 rems	0	0	+	0	0	0
Burns	1500 rems	0	0	+	0	0	0
Joksimovic	100	0	0	-	0	0	-
Kinchin		+	+	+	0	+	0
Levine		0	+	0	-	+	0
NRC	2	0	0	0	0	0	0
Wall	500 rems	0	0	0	0	0	0
Wall	0.05 LCF	0	0	0	0	0	0
Zebroski	25,000 rems	0	0	0	0	0	0

*NOTE: The performance measures used in this table may be identified as follows: 1) comprehensive; 2) unambiguous; 3) uncertainty treated; 4) practicable; 5) defensible; 6) simple.

ACRS = Advisory Committee on Reactor Safeguards
AIF = Atomic Industrial Forum
NRC = Nuclear Regulatory Commission

tiple criteria are generally derived from different assumptions and are based on different rationales. Although multiple criteria offered in any one table often have a consistent basis, multiple criteria offered in different tables consistently have diverse bases. For example, each person offering an individual risk criterion in Table 5B and also offering a societal risk criterion in Table 5C never identifies his assumptions on population distribution or meteorological conditions, both of which affect the number of mortalities. Therefore, information in Table 5C is not directly derivable from that given in Table 5B. Because multiple criteria across different tables always earn a negative rating, we do not indicate that finding in the tables.

No Proposal Considers All Aspects of Societal Risk (Comprehensiveness)

Societal risks have many facets, ranging from direct risks to indirect risks. Direct risks are those that result from direct exposure to radioactivity. Such risks may cause either immediate or delayed effects, and include risks to individuals exposed to average doses of radiation and to individuals exposed to the maximum doses. Individuals include members of the general population and the occupational work force. Indirect risks develop as a direct result of the accident and include the risks associated with evacuation (such as traffic mortalities), with accident cleanup (such as increased exposure to radiation), and with the resulting financial loss (property damage, accident cleanup costs, loss of generating capacity, decreased industrial growth, and so on).

Because no single proposal considers more than a few of these risks, a proposal need only consider a few to earn a "+" rating. Proposals that consider one or perhaps two risks generally earn a "0." A few proposals earn a "-" if they consider only immediate mortality to an individual exposed to an average dose.

Several proposals earn a "+." The Mitra et al. (1981) core-melt criteria earn a "+" because they collectively consider core melt and dollar loss and relate their criteria to the accidents at Brown's Ferry and Three Mile Island, thereby, presumably, considering both direct and indirect risks. The ACRS (NUREG-0739) proposal earns a "+" on societal and individual mortality-risk criteria for considering both early and delayed mortality. AIF (Inside NRC, 1980a), Bowen (1975), Joksimovic (1980), Kinchin (1979), NRC (Inside NRC, 1981a), and Starr (1981) each earn a "+" for individual mortality risk because they specified both delayed and early criteria. Kinchin's (1979) societal risk curves earn a "+" for considering both early and delayed effects. Maxey (1982) earns a "0" grade. Although she fails to explicitly state the extent to which her proposal covers direct and indirect risks, it would not be difficult to extend her quite straightforward criterion to consider a broader range of risks.

Most Proposals Are Explicit (Unambiguous)

For a proposal to be considered unambiguous, it must have a clearly stated rationale for nuclear power growth estimates, which includes: 1) how many years an initial set of values should be used on an interim basis; 2) if the criterion would be interpreted precisely the same way

by each person, for each design; and 3) if the criterion clearly defines the problem.

Most of the proposals receive "0" or "+" for this performance measure; a few receive "-." Proposals that received a "0" or "-" grade often did so because they imprecisely defined such critical terms as "core melt," "large-scale," and "accident."

For individual risk criteria, Maxey earns the highest "+" because of the directness of her criterion.

The evaluations made under this performance measure are particularly sensitive to the quality of information available on each criterion. Not all criteria are described at the same level of detail. Further, not all criteria in the tables are as up-to-date as one would wish, nor as precise as the author may have meant them to be.

Few Criteria Completely Accommodate Data Uncertainty (Uncertainty Treated)

The rule of thumb used in grading the proposals is to give a "+" if the proposal addresses uncertainty by considering some sort of confidence bands. A "0" rating is given if uncertainty is recognized but not treated adequately. Otherwise, a rating of "-" is given.

The proposals that consider uncertainty do so in various ways. In one proposal, Vesely provides a warning range which stipulates that it would be up to NRC's review whether or not the plant should be shut down. The warning range accounts for uncertainties in the calculation inherent in estimating the frequency of core-damage accidents. In another proposal, Vesely does not provide a warning range. Where he suggests a warning range, his criterion gets a "+"; otherwise it gets a

"0." Burns proposes an alternate in case his recommended criterion cannot be met. Because that does not fully address the question of uncertainty, it earns a "0." Starr provides an upper limit four orders of magnitude greater than his individual risk criterion, which also earns a "0." Mitra et al. (1981) give an additional individual risk criterion as a numerical parameter with a 95 percent confidence level. This criterion earns a "+."

Many Criteria Are Practicable (Practicable)

The test for practicability is simple. A proposal receives a "+" grade if several of the following conditions are met:

1. Time test: If the criterion has been applied implicitly to the nuclear industry sometime before, it would be considered a de facto criterion that is "acceptable." This condition applies, for example, to core-melt criteria, as well as to the $1,000 per person-rem interim cost-benefit criterion of the NRC Rules and Regulations (Appendix I of the Code of Federal Regulations, Part 50).
2. Relates to other industry: Is the criterion based on an adaptation of what might already have been time-tested in another industry? If so, we may be better able to determine whether the criterion is transferable to the nuclear power industry. However, as Salem et al. (1980) explain, the extent to which criteria are transferable across industries, especially the nuclear industry, is uncertain.

3. Sufficiently lenient: Criteria would not be considered practicable if they were so stringent that new reactor designs that use the best and most current safety systems would be unable to meet them. However, older reactors might be exempted from such newer criteria; for example, NUREG-0739 applies to new reactors only.

4. Too lenient: Criteria that are too lenient would be inherently unacceptable by the NRC.

Even when set against these four conditions, most criteria earn a "+" grade. Maxey (1982) again earns a very high "+" because of the time-tested nature of her criterion. A few outliers earn a "-" grade for being too lenient or too stringent. (Such definitions of lenient and stringent are, of course, highly subjective.)

No Criterion Can Always Be Defensible

Criteria that are defensible are criteria that are formed on some rational basis. For example, they must detail their evolution, be developed from some accepted or acknowledged standard, and consist of detailed, highly supportable assumptions. For purposes of ranking, unsupportable assumptions would be considered the same as no basis at all.

Many criteria earn a "0" because they are only moderately defensible, providing only some limited basis for the rationale behind the criterion. Adams and Stone (1967) contend that the risk is acceptable if the risk from nuclear plants falls below that of the natural demographic variation in the United Kingdom (U.K.). No numerical parameter was

presented, however. Maxey earns a "0" for a similar reason. Mitra et al. (1981) limit their bases to past operating experience in the nuclear industry; no theoretical basis is given.

The criteria tend to be more a matter of judgment than scientifically backed findings. For instance, Kinchin's rationale for his early death-limit curve was: "It would not seem unreasonable to propose a criterion that the total risk from nuclear reactors should be roughly comparable with that from meteorites." Each of an assumed population of 100 reactors in the U.K. was assigned 1/100 of the total risk. The societal delayed-death curve was formed using the same factor of 30 used to set the limit on individual delayed-death risk (Kinchin, 1979).

Levine (1981) discussed the rationale behind each of several proposals that we have evaluated here. He summarized the rationale used to develop the three factors that we have discussed: core melt, individual risks, and societal risks. We have condensed the rationales for several of these proposals into tabular form; they are presented in Table 6. We have not used this table as a separate means of augmenting the rankings presented in Table 5. Rather, we compared each individual rationale to that given in the original source for each criterion, and used the combined information to arrive at the rankings in Table 5. Notice that several of Levine's own criteria are not presented in Tables 1-5. These were not included in our original sampling of criteria (in this case, Levine, 1980), and we have not yet attempted to evaluate any criteria published after mid-1981.

Table 6

RATIONALE FOR FORMULATING PROPOSALS FOR THE CRITERIA

PROPOSAL	FACTOR		
	CORE MELT	INDIVIDUAL RISK	SOCIETAL RISK
(NUREG-0739)	Keep frequency < TMI-2 or < 1 per 100 R-Y	Smaller than background No basis on delayed death	Delayed death based on coal plants Early deaths. 20% of delayed
(AIF, 1981)	NA (not applicable)	Smaller than background	Comparable to other energy production
(Joksimovic, 1980)	NA	Uses both EPA rules & Appendix I of 10 CFR 50	Small increase over background. Cancer following an accident
(Starr, 1981)	NA	For people far from plant. Same as background For people near plant, 100 times greater risk	NA
(Levine, 1981)	A factor of 50. More lenient than WASH-1400	Factor of 1/30 of equivalent early fatalities. Based on worker preference data	Curve is 0.1% of sum of all man-made accidents May raise this by factor of 10
(Kinchin, 1979)	NA	Early deaths based on ICRP Factor of 30 less stringent for delayed deaths. Based on intuition	Early deaths. Based on meteorite impact probability

Table 6 (cont.)

PROPOSAL	FACTOR		
	CORE MELT	INDIVIDUAL RISK	SOCIETAL RISK
(Bhattacharyya, 1981)	Uses maximum equivalent hazard state	No distinction between delayed and early deaths Small compared to background	Expected values to maximum exposed individuals No weighting for large consequence Small population around sites
(NUREG-0739)	No basis given	Small compared to background	Consistent with risk from coal
(WASH-1400)	Varied	Varied	Varied

NOTE: The parenthetical entries in the PROPOSAL column correspond to similar entries in the References.

An Overly Simplified Criterion May Lack Credence (Simple)

Although simplicity can be thought of as a positive attribute, simplistic criteria often are indefensible, do not account properly for uncertainty, and are ambiguous. Simple criteria are unconditional and do not depend on many factors, but are readily understood by most of those who use them. Adams and Stone (1967) simply relate acceptable incremental risk to demographic variations, which can be measured and used as a guideline. This earns a "+" for simplicity. Burns (1979) allows for a 5 percent chance of core melt in 100,000 reactor years. On the positive side, the numbers are simple, easy to understand, and commonsensical. On the negative side, Burns' criteria do not deal ade-

quately with uncertainty. Burns earns a "+" for simplicity and a "0" for dealing with uncertainty.

It is clear that criteria which are comprehensive, defensible, and treat uncertainty will almost certainly be more complex than those which do not. Therefore, our ranking of the simplicity of any criterion is somewhat subjective--a criterion that meets most other performance measures is expected to be less simple and need not earn a "-" just because it is detailed. The details themselves must be clearly stated. Thus, a complex but precisely detailed criterion would be considered simpler than a short but unintelligible or poorly defined one.

Internally Inconsistent Criteria

A criterion can have no internal consistency if it is presented in more than one table. How we judge this internal inconsistency is quite simple. We look at the criterion offered for, say, core melt and from that derive the individual risk criterion and the societal risk criterion. Because assumed population distributions and meteorology conditions were not given, the numbers that we derived did not match what was offered by others.

SUMMARY

Although these evaluations reveal numerous findings specific to a variety of criteria, they identify three trends generic to most or all criteria:

1. Little consensus exists on a universal risk criterion. That lack of consensus underscores the highly subjective nature of

the criteria selection process, a process that may not yield one single, universally accepted criterion.

2. No single criterion is both simple to understand and easy to implement. Further, no apparent mechanism for implementation is generally offered.

3. None of the criteria can adequately accommodate uncertainty in the data. Although uncertainty must be bounded, it is inherent in any complex system and cannot be eliminated. Uncertainty must be treated systematically.

Under what conditions are these proposals most applicable? Before answering that question, the five shortcomings discussed earlier must be overcome: 1) the performance measures are not concretely definable; 2) they do not encompass the entire range of valuation measures; 3) the relative importance of one measure compared to another is subject to value judgment; 4) each criterion is differently documented and understood; and the 5) evaluation process is highly subjective. Were it not for those five shortcomings, the criteria might be ranked in descending order by identifying as best those criteria awarded the most "+"es and the least "-"es. Thus, Maxey, the ACRS, or Mitra might be the winners.

In view of the shortcomings, however, there are only three things we can do: 1) ignore the evaluation; 2) permit the evaluator to substitute his or her own performance measures and weights; or 3) attempt to develop a hybrid criterion or set of criteria made up of the best features of each proposal. The first alternative requires no action, the second requires action only by the interested reader. The third requires the kind of assessment we discuss in the section that follows.

IV. CAN WE DEFINE AN OPTIMAL RISK CRITERION?

This section is divided into four subsections. First, we address the question of whether we can define an optimal criterion. Second, we qualitatively describe the features of the hybrid we recommend. Third, we quantify that hybrid. And fourth, we present a rationale for that hybrid.

CAN WE DEFINE AN OPTIMAL CRITERION?

The answer to that question is, simply, no. Our evaluation merely segregates each of the criterion into three rating groups, ranking them in relation to one another. At best, this approach assures only that we can separate the better criteria (based on a set of performance measures) from all others; it in no way implies that we can discover the best criterion (if one is, theoretically, even possible).

In applying the performance measures to each of the proposed criteria, we found that no single criterion received a "+" grade on all measures. In fact, only a few criteria earned three or four out of six "+" grades, and only the core-melt criteria of Mitra et al. (1981) received five out of six "+" grades. We speak of only six performance measures because the seventh measure, internal consistency, always leads to "-" for multiple criteria.

Based on this finding, can we arrive at a hybrid criterion or set of criteria that incorporates the best features of each of the proposed criteria? If so, this hybrid criterion's features would resemble closely the specifications outlined for each performance measure and as

such would have the same shortcomings. With regard to each performance measure, this hybrid would have a number of specific qualitative features.

THE HYBRID CRITERION: A QUALITATIVE DESCRIPTION

The hybrid criterion would comprehensively address societal risk. It would be concerned with both immediate and delayed mortality and would consider not only the individual exposed to an average level of risk, but also those exposed to higher levels. This hybrid criterion might also address the issue of secondary effects from the risk. (Such risks as those that might result from evacuation, accident cleanup, and job relocations would be considered valid secondary risks.) One could successfully argue that more people might die as a result of traffic accidents while evacuating from the site of a nuclear accident than would die as a direct result of the accident for less than catastrophic core melts. Although each of these secondary risks might complicate the criterion, a criterion that specifies a common denominator of equivalent early and equivalent delayed mortalities from all causes would more equitably reflect the total risk and would be judged more sound.

Of the proposed criteria, only those of Mitra et al. (1981) partially consider secondary costs; several individuals consider delayed mortality, and only a few consider the people most exposed. Specifically, Mitra et al. (1981) address the problem of replacement power costs but fail to consider secondary mortalities. The ACRS (NUREG-0739), Griesmeyer et al. (1979), Kinchin (1979), Bowen (1979), and several others distinguish between delayed and immediate mortality.

This hybrid would be both simple and unambiguous. A simple criterion might be described as one that is intuitive or commonsensical and does not depend on many complicating conditions. However, an unambiguous criterion might be described as one that explicitly states each assumption and condition upon which it is based. Few criteria are both explicit and simple. The two criteria of Mitra et al. dealing with core damage and replacement power costs following a core melt are both explicit and simple.

This hybrid would account for uncertainty in the data base and the PRA methodology. Vesely, Starr and Whipple, Mitra et al., Zebroski, the ACRS, Atchison, and Joksimovic each accommodate for uncertainty in either PRA methodology, data base, or both. Vesely provides warning ranges; Starr and Whipple provide an upper limit four orders of magnitude greater than his mean; and Mitra et al. specify a 95 percent confidence limit. Zebroski's core-melt criteria reflect differing assumptions about reactor years assumed to be operating over the next twenty years. The ACRS bounds their individual mortality risk criteria by setting an upper limit and a goal level. Atchison specifies a range for latent thyroid fatalities. None of the other proposals accommodates for uncertainty to such an extent.

This hybrid would be practicable. Many of the proposed criteria are practicable; that is to say, they either do not ask for the impossible or they have been used before.

The hybrid would be defensible. The more defensible criteria are based on some rationale that uses past experience either within the nuclear industry or in another industry with accident scenarios of simi-

lar potential. The more defensible criteria clearly specify each of their assumptions. For core-melt criteria, Mitra et al. base their two proposals on relevant past experience.

Levine (1981) outlines each factor judged important in setting safety goals. His factors very clearly complement and support the qualitative description of the hybrid criterion that we have just outlined, and, as such, are summarized below. We endorse each of his ten points.

1. The goals should have three purposes: to help ensure adequate protection of the public; to help make the regulatory process more rational; and to be easily understood by a broad spectrum of society.
2. The criteria should be used expressly as goals, not as regulatory requirements specifically applied to individual reactor-licensing cases.
3. The goal should be such that it does not contribute significantly to the sum of existing risk. Also, comparisons between safety goals and other risks must be made on the basis of more than just average risk.
4. A high degree of specificity should be avoided.
5. Early and latent fatalities should be combined so that future mortalities are not discounted.
6. Individual and societal risks and core-melt probabilities should be stated explicitly.
7. Engineering factors are of secondary importance compared to health effects.

8. Engineering factors with high calculational uncertainty should be avoided.
9. Cost-benefit criterion in dollars per person-rem should be included.
10. Nuclear risks should not be disproportionately weighted in relation to other risks.

THE HYBRID CRITERION: A QUANTITATIVE DESCRIPTION

Quantitatively, what should this hybrid criterion look like? We would require some level of certainty on calculated data. This level of certainty ought to be less than 100 percent. We cannot determine its precise value at this time. Mitra et al. suggest a 95 percent level of certainty; we have no reason to dispute this number.

We suggest the following quantitative values. For the probability of core melt per R-Y, this hybrid might range between 1.0E-3 and 1.0E-4. For marginal increase in an individual's annual mortality rate, it might range between 2.0E-5 and 1.0E-6 per R-Y. For societal risk measured in person-rems, the range might be between 1000 and 10,000 per R-Y through about the year 2000. At that time, and depending on the size of the nuclear power industry, this number would have to be reevaluated.

THE BASIS FOR OUR HYBRID CRITERION

To determine that basis, we must first ask two pragmatic questions: How did we arrive at the quantitative values? How did we arrive at the qualitative description?

The basis for our quantitative range is simple and highly subjective. We consider those criteria that earn the most "+"es and least "-"es, group them, and specify the range in values that this group covers.

Outliers are discarded if the range is much beyond a certain order of magnitude. The basis for our qualitative criteria is far more complex to describe. Point by point, we here describe that basis.

Why Address Societal Risks Comprehensively?

We believe that all components of a risk, including direct and indirect risks and immediate and delayed risks, are necessary for deciding between alternative criteria. A primary purpose of establishing a criterion is to assist in deciding which of several viable alternatives is the least risky. Because each alternative brings with it both direct and immediate risks as well as indirect and delayed risks, we contend that any sound decision must include those factors.

Do Not Discount Future Risks Too Heavily

We judge that the rate at which future risks are discounted is an important element of any acceptable risk criterion.

Although identifying a proper discount rate is far beyond the scope if our work, we can identify a simple ground rule for selecting this factor: it should account for all future risks, especially risk criteria for waste disposal. This argues for a small discount rate or a modest rate for near-term risks and a zero or near-zero rate beyond a couple of generations.

Although we are unwilling to offer what we think is a reasonable factor for discounting future risks, we dispute the larger factors, for three reasons. First, they tend to be inconsistent. Second, the discount factor seems so high that risks more than a couple of genera-

tions into the future are not likely to be counted. Third, the discount factors that were offered do not appear to be based on any sound reasoning.

Why Use Simple Criteria?

The more conditional the criterion, the more subject it would be to ambiguous interpretation. Highly conditional criteria might offer more opportunity for equitable standards, but to those who need to interpret and enforce these criteria, they present more subjective information.

Include Uncertainty

Any valid criterion must recognize the potential for uncertainty that must be considered when compounding calculations needed to fulfill any PRA. The mechanism for including uncertainty would consist of identifying a range rather than a single criterion. This range would require that some band of confidence be met, suggesting that all future PRA calculations carry with them a standard for propagating uncertainty.

Criteria requiring repeated calculations that would accumulate uncertainty must be avoided. Wide uncertainty bands would tend to dilute the issues rather than reinforce the criterion.

Select a Proven Criterion

Criteria that have been proven or time-tested are generally more appealing than those that are merely deduced. When both time-tested and simple, a criterion like Maxey's (risk should be equal to the variance in background radiation level across the country) is quite attractive.

Maxey's inferred value of 2.0E-5 fatality rate per R-Y reflects the least restrictive bound of our hybrid criterion.

Avoid Risk Aversion

We argue against including risk aversion as part of the hybrid criterion. If all direct and indirect components of the risk are considered, then including some risk aversion for nuclear power is unjustifiable. That is to say, by properly accounting for all indirect risks of nuclear power and by selecting a rational discount factor for future risks, including some additional risk aversion factor is double counting.

Human Health is of Primary Importance

The hybrid should be primarily concerned with maintaining human health and secondarily concerned with engineering considerations and property damage. This reasoning argues for placing a high value on human life and making some cost/benefit decisions in meeting design standards that ensure that this concern will be an integral part of any potential safety criterion.

REFERENCES

(Inside NRC, 1980a) "ACRS' Moeller Outlines Safety Goal," Inside NRC, Vol. 2, No. 12, June 16, 1980, p. 6.

(Adams & Stone, 1967) Adams, C. A., and C. N. Stone, "Safety and Siting of Nuclear Power Stations in the United Kingdom," IAEA Symposium on the Containment and Siting of Nuclear Power Plants, Vienna, April 1967.

(Inside NRC, 1980b) "AIF Group Presents Proposal," Inside NRC, Vol. 2, No. 23, November 17, 1980, pp. 14-15.

(NUREG-0739) "An Approach to Quantitative Safety Goals for Nuclear Power Plants," NUREG-0739, U.S. Nuclear Regulatory Commission, Advisory Committee on Reactor Safeguards, October 1980.

(AIF, 1981) "A Proposed Approach to the Establishment and Use of Quantitative Safety Goals in the Nuclear Regulatory Process," Draft report, Atomic Industrial Forum, New York, March 26, 1981.

(Atchison, 1979) Atchison, R. J., "Nuclear Reactor Philosophy and Criteria," presented to Select Committee on Ontario Hydro Affairs, Hearings on the safety of nuclear reactors, July 18, 1979.

(Rowsome, 1980) "Backfit Deadlines Based on Hypothetical Interim Acceptable Risk Numbers," Memorandum from F. H. Rowsome to NRC to R. M. Bernero, NRC, July 11, 1980.

(Bhattacharyya, 1981) Bhattacharyya, A., "Summary of Safety Goal Proposals," Professional Correspondence, KULJIAN Corporation, Philadelphia, Pennsylvania, March 16, 1981.

(Bowen, 1975) Bowen, J., "The Choice of Criteria for Individual Risk, Statistical Risk, and for Public Risk," in D. Okrent (ed.), "Risk Benefit Methodology and Application," Paper presented at the Engineering Foundation Workshop, Asinlomar, California, September 22-26, 1975.

(Burns, 1979) Burns, R. D., "Proposed Criteria for Risk Assessment," Energy Division, Los Alamos Scientific Laboratory (in response to a letter from W. E. Vesely of the USNRC), March 1979.

(Code of Federal Regulations) Code of Federal Regulations, 10 CFR 50, "Licensing of Production and Utilization Facilities," Washington, D.C., U.S. Government Printing Office, January 1, 1979.

(Griesmeyer, 1979) Griesmeyer, J. M., M. Simpson, and D. Okrent, "The Use of Risk Aversion in Risk Acceptance Criteria?" UCLA-ENG-7870, University of California, Los Angeles, October 1979.

(Nucleonics, 1980b) "IAEA Progressing on Establishment of Safety Standards," Nucleonics Week, Vol. 21, No. 29, July 31, 1980, p. 6.

(Joksimovic, 1980) Joksimovic, V., "Statement of Quantitative Safety Goals before ACRS subcommittee on Reliability and Probabilistic Assessment," Paper presented to the Advisory Committee on Reactor Safeguards of the Nuclear Regulatory Commission, General Atomic Company, La Jolla, California, July 1980.

(Kaplan, 1981) Kaplan, S., "On Safety Goals and Related Questions," Report prepared for Nuclear Safety and Analysis Center of the Electric Power Research Institute, February 1981.

(Kinchin, 1979) Kinchin, G. H., "Design Criteria Concepts and Features Important to Safety and Licensing," Presented at the ANS/ENS International meeting on Fast Reactor Safety Technology, Seattle, Washington, November 1979.

(Levine, 1980) Levine, S., "TMI and the Future of Reactor Safety," Presented at International Public Affairs Workshop (AIF), Stockholm, June 1980.

(Levine, 1981) Levine, S., "Summary and Analysis of Safety Goal Proposals," Report 3871, NUS Corporation, September 1981.

(Nucleonics, 1980a) "Licensing Guide To Be Issued," Nucleonics Week, Vol. 21, No. 16, April 17, 1980, p. 11.

(Maxey, 1982) Maxey, Margaret, Personal communication, University of Texas, School of Engineering, Chair on Free Enterprise, February 1982.

(Mitra, 1981) Mitra, S., R. Hall, and A. Coppola, "A Study of the Implications of Applying Quantitative Risk Criteria in the Licensing of Nuclear Power Plants in the United States," BNL-NUREG-51367, Brookhaven National Laboratory, March 1981.

(Inside NRC, 1981a) "NRC Safety Goals," Inside NRC, Vol. 3, No. 15, July 27, 1981, p. 4.

(OTA, 1981) "Nuclear Power Plant Standardization: LWR," Office of Technological Assessment, 97th Congress, November 1981.

(WASH-1400) "Reactor Safety Study, an Assessment of Accident Risks in United States Commercial Nuclear Power Plants," USNRC, WASH-1400 Study, NUREG-75/014, Appendix 6, Washington, D.C., U.S. Government Printing Office, October 1975.

(Salem, 1980) Salem, S. L., K. A. Solomon, and M. S. Yesley, "Issues and Problems in Inferring a Level of Acceptable Risk," R-2561-DOE, The Rand Corporation, August 1980.

(Slovic, 1980) Slovic, P., B. Fischhoff, and S. Lichtenstein, "Setting Acceptable Risk Criteria and Decision Making," In the transactions of the American Nuclear Society, Vol. 35, 1980, pp. 400-401.

(SRP, 1975) "Standard Review Plan for Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition," Appendix 7-A Branch Technical Position BTP E1CSB 2, Diesel-generator qualification testing, NUREG-75/087, P.B. 247611, Washington, D.C., U.S. Government Printing Office, September 1975.

(Starr, 1981) Starr, C., and C. Whipple, "Coping with Nuclear Power Risks: The Electric Utility Incentives," Draft paper, Electric Power Research Institute, Palo Alto, California, July 28, 1981.

(Nucleonics, 1980c) "There Haven't Been Enough Accidents to Gain Experience," Nucleonics Week, Vol. 21, No. 9, February 28, 1980, p. 3.

(Vesely, 1980) Vesely, W. E., "Numerical Risk Criteria," Presented to the ACRS PRA subcommittee meeting, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, D.C., April 30, 1980.

(Wall, 1979a) Wall, I. B., "Probabilistic Risk Assessment in Nuclear Power Plant Regulation," Paper presented at the Second International Seminar on Structural Reliability of Mechanical Components and Subassemblies of Nuclear Power Plants, Berlin, West Germany, August 1979a.

(Wall, 1979b) Wall, I. B., "What ATWS Risk Would Be Cause for Concern?" Presented to ACRS/ATWS subcommittee, Washington, D.C., July 1979b.

(Zebroski, 1980) Zebroski, E. L., "A Proposed National Nuclear Safety Goal," Presented at the Seventh Energy Technology Conference, Washington, D.C., March 24-26, 1980.

NOTE: The parenthetical material that precedes each entry in this list corresponds to and serves to identify incomplete reference citations in the tables throughout this document.

RAND/N-1806-ORNL